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ICE SHEET ALTIMETRY

P. L. Brooks

GeoScience Research Corporation  
Route 4 Box 129  
Salisbury, Maryland 21801



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## INTRODUCTION

NASA Wallops Flight Center is currently designing an improved ice sheet tracking capability to be incorporated into future satellite altimeters. The GeoScience Research Corporation (GSRC) has been assisting Wallops Flight Center personnel in their endeavor by providing ice sheet topography parameters and evaluating the Seasat altimeter performance over the ice sheets. The following is a summary of GSRC studies performed for NASA under Task 3 of Contract NAS6-3117.

## ICE SHEET SURFACE SLOPES

Knowledge of the surface dynamics of the Antarctica and Greenland ice sheets is of prime importance for designing a future altimeter tracking capability. To add to the knowledge of ice sheet surface dynamics, generalized surface slopes were computed from the best ice sheet contour maps available.

The surface slopes for Antarctica are shown in Figure 1. The surface slopes (  $0.1^\circ$ ,  $0.2^\circ$ ,  $0.5^\circ$ ,  $1.0^\circ$ ,  $>1.0^\circ$  ) were determined by differencing plotted contour levels and dividing them by the distance between the contours. The map used for the computation was the Antarctica sheet by the American Geographical Society of New York prepared under a National Science Foundation grant. The map scale is 1:5,000,000 and the contour interval is 500 m.

The surface slopes for Greenland were derived in a similar manner and are illustrated in Figure 2. The map utilized for Greenland was the USAF Jet Navigation Chart JNC 4A with a scale of 1:3,000,000 and a contour interval of 610 m (2000 ft).

These ice sheet slopes are very generalized since only very long wavelengths were involved in their computations but they should be useful for mission planning. It is observed that more than 90% of the ice sheets have surface slopes less than  $1^\circ$ . It is recommended, therefore, that the ice sheet tracking design effort consider only slopes less than  $1^\circ$ .

FIGURE 1

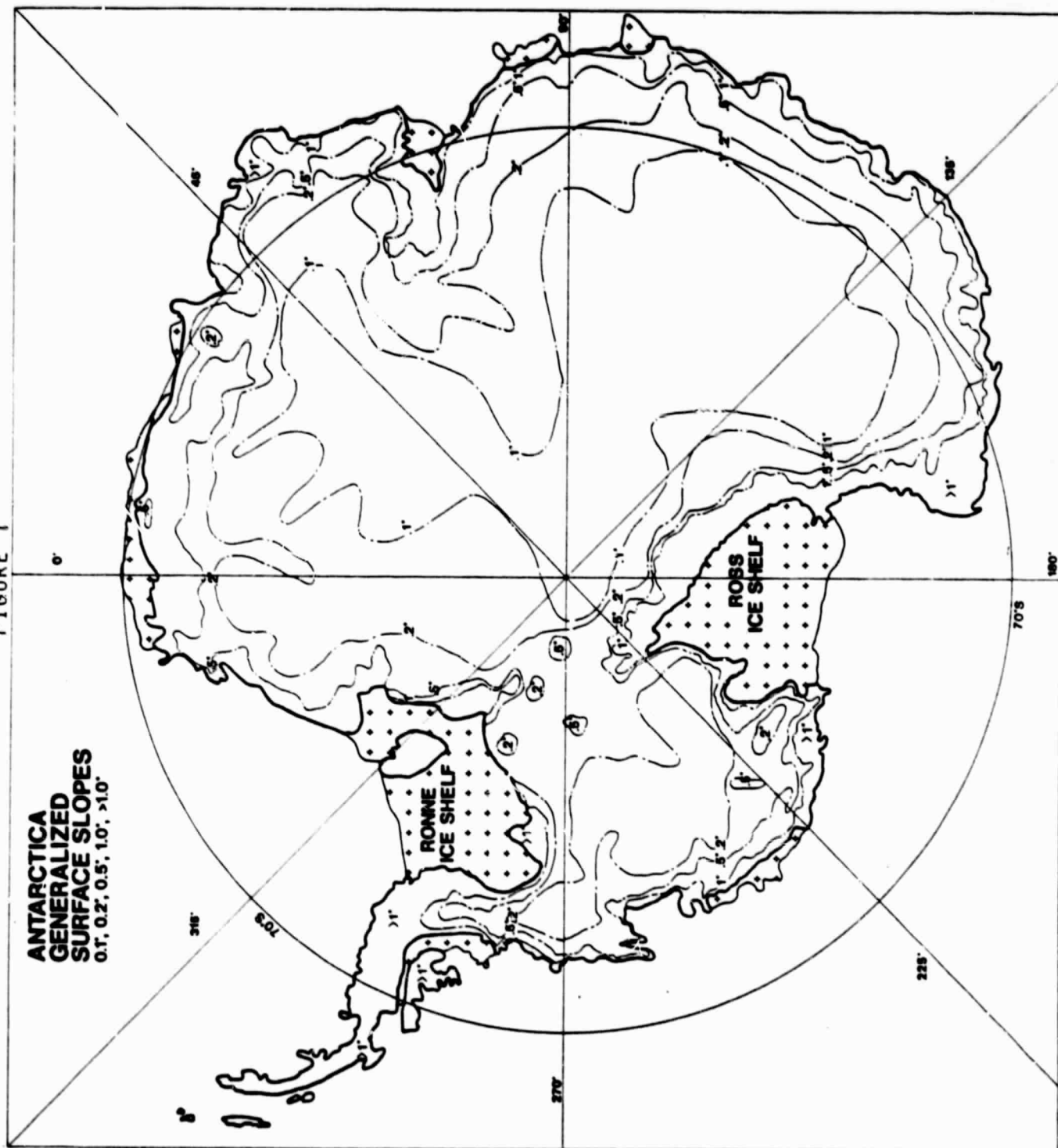
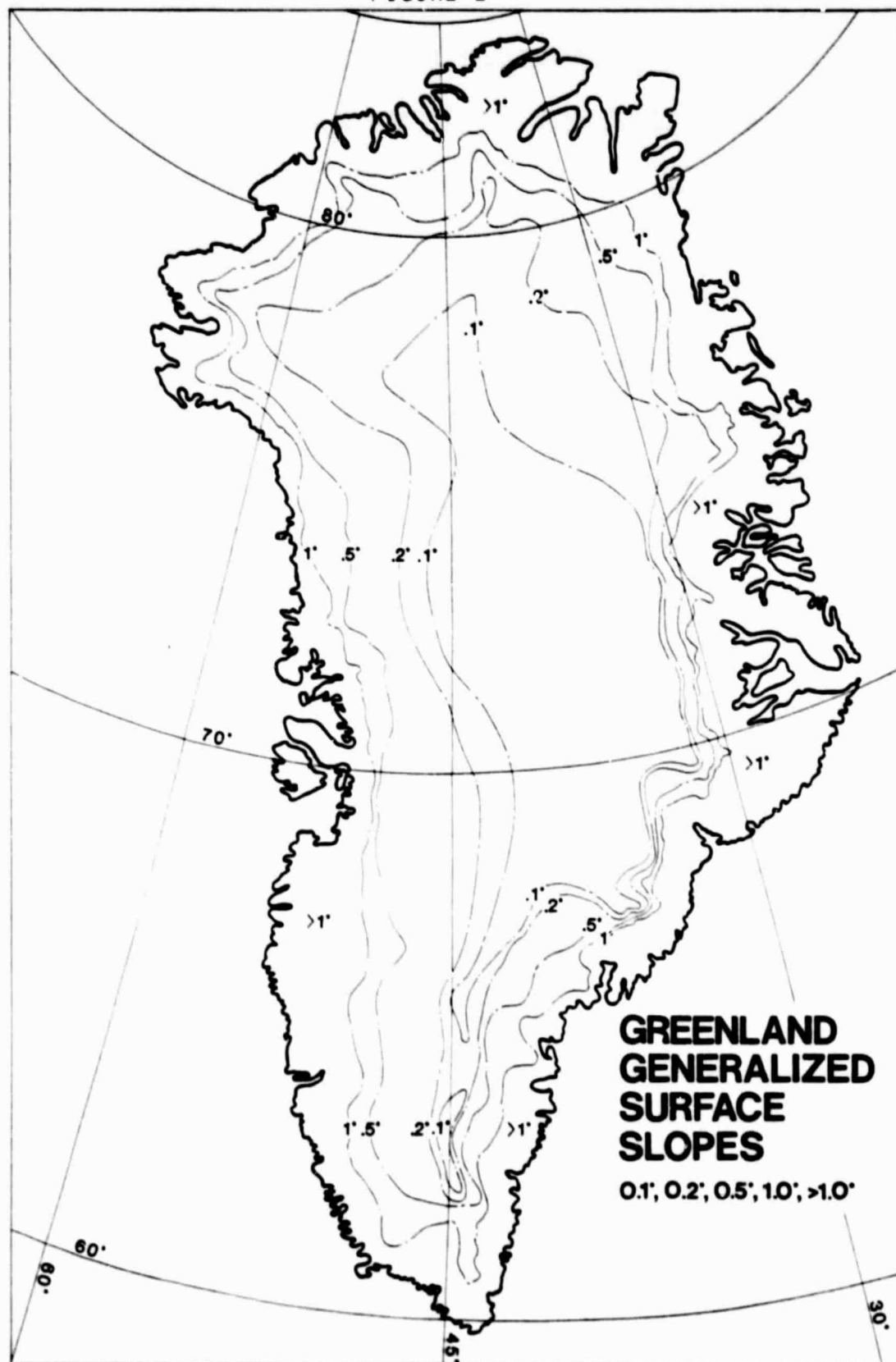


FIGURE 2



Histograms of ice sheet surface slopes have been provided to WFC by Goddard Space Flight Center (GSFC) without accompanying information on how the statistics were derived, or the associated uncertainties. We devised a straightforward equal-area method to verify the GSFC-provided statistics. Average surface slopes have been determined for the Antarctica quadrant from 0° to 180° E longitude; comparison with the GSFC results is as follows:

<u>SLOPE</u>	<u>Percent Area 0-180° (GSFC)</u>	<u>Percent Area 0-180° (GSRC)</u>
<.003 (0°-0.17°)	70	56
.003 - .006 (0.17°-0.34°)	8	15
.006 - .008 (0.34°-0.46°)	1	5
.008 - .010 (0.46°-0.57°)	1	4
>.010 ( 0.57°)	18	14
Ice Shelf (0°)	2	6

The GSFC histograms, based on our independent calculations for East Antarctica, are sufficiently reliable for mission planning purposes.



## TEST-MODE-1 ICE SHEET PERFORMANCE

Test-Mode-1 Seasat altimeter measurements over Greenland were analyzed by comparisons with collinear and intersecting normal-mode Seasat altimeter passes. Over the ice sheet, the computed surface elevations from Test-Mode-1 measurements were consistently lower by about 45 m. and the AGC levels were down by approximately 6 dB. Comparison of four collinear Test-Mode-1 passes with one normal mode pass resulted in the following bias and noise estimates:

$$-46.2 \pm 8.7\text{m.}$$

$$-41.2 \pm 10.5\text{m.}$$

$$-46.4 \pm 11.2\text{m.}$$

$$-48.3 \pm 12.4\text{m.}$$

The Seasat Test-Mode-1 measurements over Greenland are useful for measuring gross features of the ice sheet in areas where the normal mode could not maintain lock.

No Seasat Test-Mode-1 data were acquired over Antarctica.

## ALTIMETER AGC VALUES OVER EAST ANTARCTICA

Seasat altimeter AGC values for East Antarctica are shown in Figure 3. Each value is the result of averaging individual AGC levels in its neighborhood. The individual AGC levels were from 15 well-distributed Seasat passes across the ice sheet. It is noted that the AGC values for the ice sheets are generally 2-3 dB lower than open-ocean values.

During this analysis, it was observed that (except for the ice shelves) the large AGC differences across the ice sheets are generally not due to differences in surface reflectivity, but result from surface slope changes causing the waveform to move with respect to the tracking gate. For a positive slope change, the AGC increases as the waveform moves toward the -30 gate and thus involves more of the waveform sampling gates. In the case of a negative slope, the AGC decreases as the waveform moves in the opposite direction and is sampled by fewer of the gates.

Figure 3 - Seasat Altimeter  
AGC Values for East  
Antarctica.

The map shows the East Antarctic region with a grid of AGC values. The values are distributed as follows:

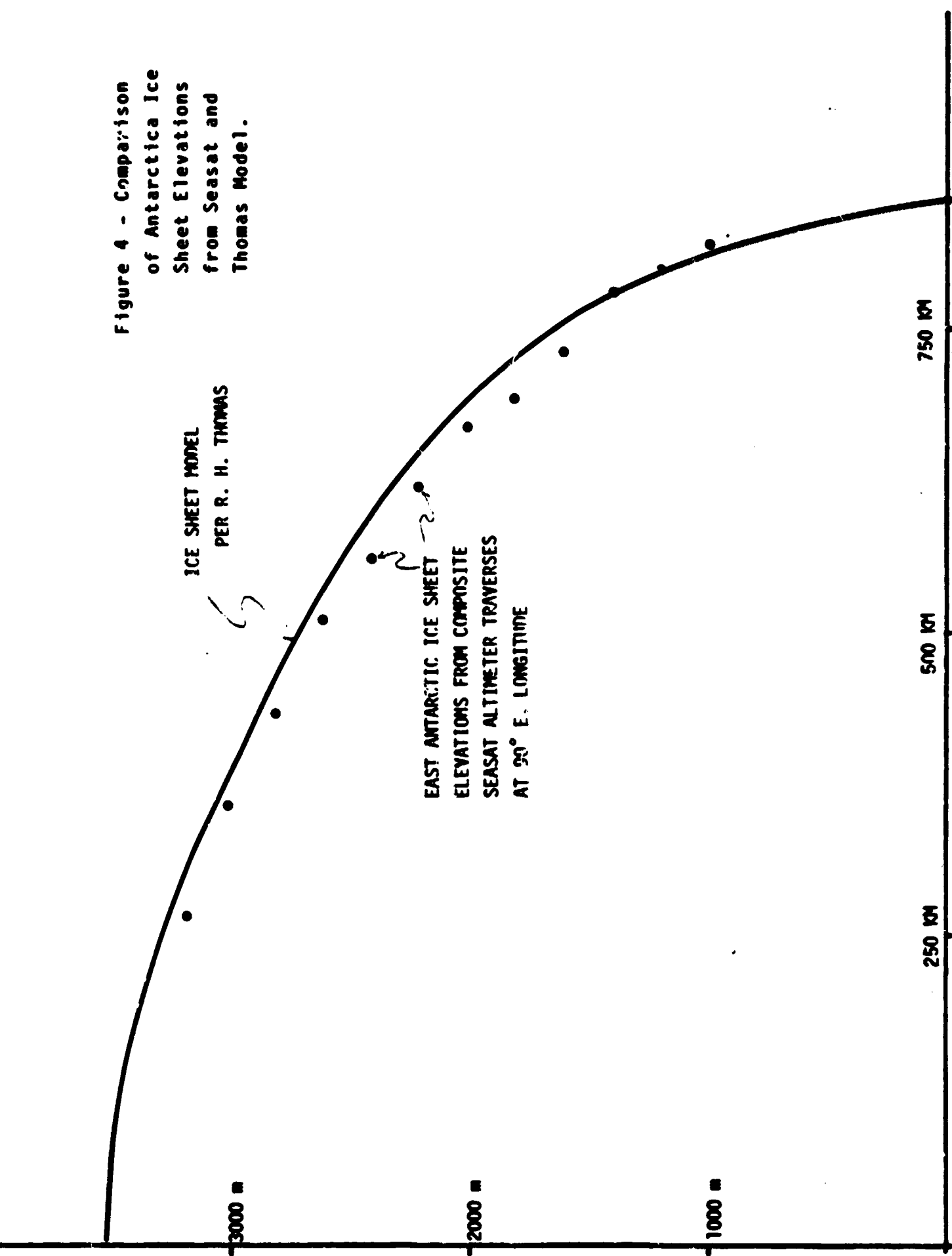
Latitude	140°E	150°E	160°E	170°E	180°E
65°S	29	30	28	28	28
64°S	29	31	27	28	28
63°S	29	29	28	27	28
62°S	29	28	28	27	28
61°S	29	28	28	28	28
60°S	27	27	28	28	28
59°S	29	30	30	27	27
58°S	29	30	30	30	24
57°S	30	31	28	28	31
56°S	29	29	30	30	30
55°S	28	28	28	28	28
54°S	27	28	28	28	28
53°S	28	28	28	27	27
52°S	24	25	25	28	28
51°S	28	24	25	27	27
50°S	30	27	28	30	30
49°S	28	29	27	31	31

## GENERALIZED ICE SHEET PROFILE

During a visit to WFC, glaciologist R. H. Thomas provided a theoretical model representing the topographical features of an ice sheet. GSRC compared this theoretical model with the Seasat-derived surface elevations.

The comparison is illustrated in Figure 4 where the solid line is the plot of theoretical surface elevation in meters (vertical axis) versus the distance in kilometers from 75°S latitude (horizontal axis). The altimeter-derived elevations are from composite Seasat traverses at 90°E longitude. The surface elevations from the Thomas model are within 10% of the Seasat-derived elevations.

Figure 4 - Comparison  
of Antarctica Ice  
Sheet Elevations  
from Seasat and  
Thomas Model.



## SEASAT WAVEFORM RETRACKING NEAR LOSS-OF-LOCK

The Seasat altimeter lost lock very frequently over the ice sheets. A typical Antarctic ice sheet profile from Seasat is plotted in Figure 5; only the in-track portion of the altimeter data is shown. In this Figure, the satellite direction was left-to-right. The altimeter was locked-up on the Pacific Ocean, but lost lock upon encountering Antarctica. Very little track data were acquired over the upslope portion of the ice sheet. Near the 3000 m elevation, the ice sheet became more level and the altimeter performed better, but still frequently lost lock. On the downslope, the altimeter very frequently lost lock although the downslope performance was far superior to the upslope performance. Good tracking resumed over the Indian Ocean.

Thorough examination of the ice sheet altimeter waveforms leads to the following conclusions:

- 1) The altimeter's pre-programmed acquisition algorithm was primarily responsible for the lack of measurements on the ice sheet upslope. The acquisition system performed its design role, that of open-ocean acquisition, very well, but couldn't accommodate a rising surface.

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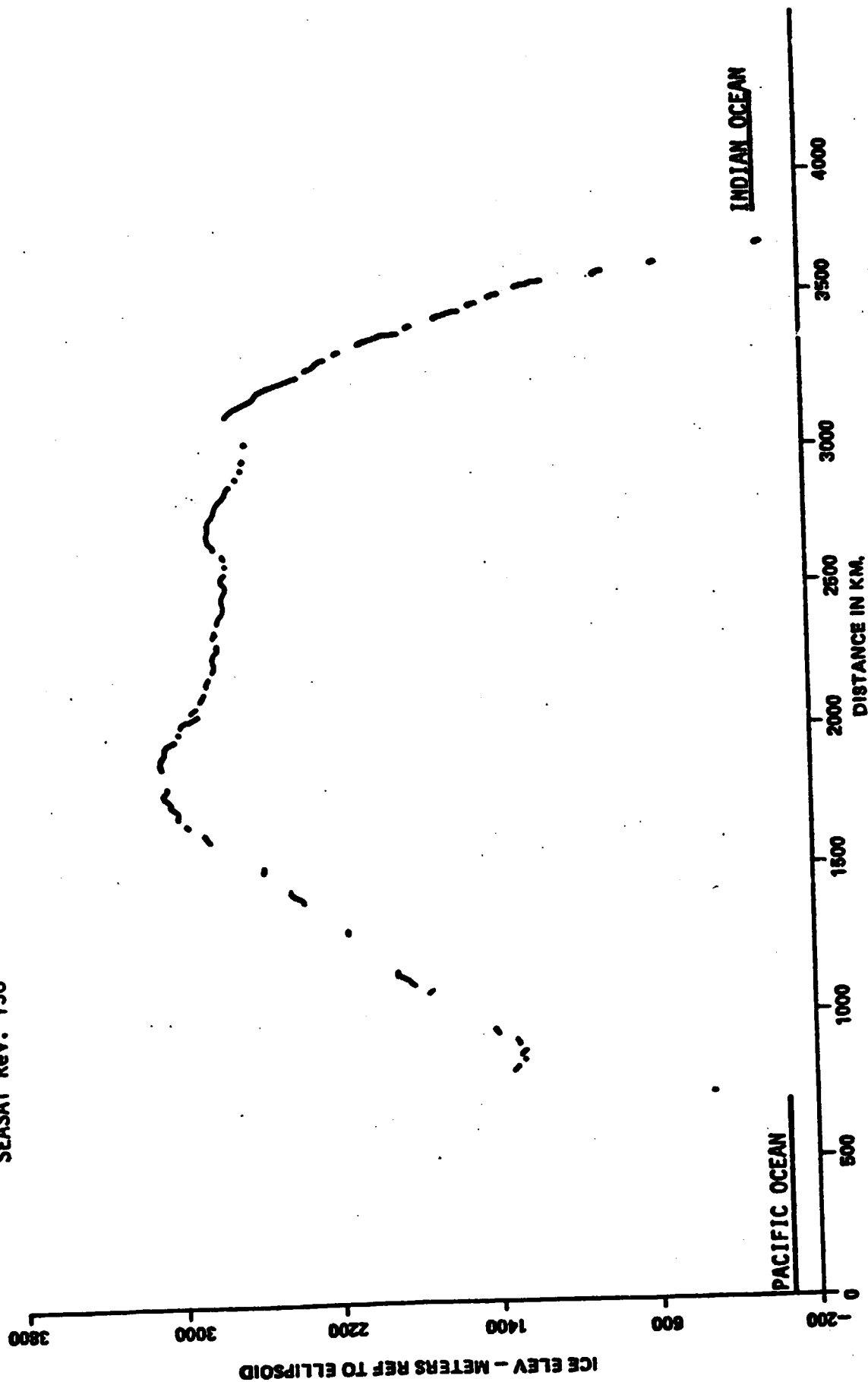


Figure 5 - Typical Antarctic Ice Sheet Profile from SEASAT Altimetry

2) The losses-of-lock on the downslope and the more level upper elevations, are due almost exclusively to changes in the surface slope and the altimeter's failure to respond to these changes. The slope changes are the result of surface waves, and are more prevalent at lower elevations. Changes in the surface height rate cause the wave-forms to move with respect to the waveform sampling gates. If the height acceleration exceeds the response capability of the tracker and if the condition persists, the waveform will walk-out of the sampling gates and the altimeter will lose lock. The loss of lock occurs when the height acceleration results in a 14.05 m (30 gates) disparity between the sluggish on-board tracker and the true surface.

Retracking of the altimeter near the loss-of-lock areas of the ice sheets reveals the nature of the surface waves. The retracking was accomplished by repositioning the tracking point at the 50% power point on the waveform ramp immediately preceding the peak power point.



One result of retracking the Seasat waveforms is shown in Figure 6 where a normal mode traverse of Greenland lost lock at the 14 km mark and where a subsequent Test-Mode-1 pass with essentially the same groundtrack tracked through the loss-of-lock area. The dashed line terminating at the 14 km mark represents the surface elevations from the normal mode onboard tracker; the solid line depicts the surface elevations from the retracked waveforms. These normal-mode data are from Seasat revolution 889 on August 28, 1978. The latitude and longitude at the loss-of-lock are  $69.59^{\circ}$  N and  $46.75^{\circ}$  W, respectively. The Test-Mode-1 data are from revolution 1147 on September 15, 1978. An elevation bias correction of 50 m. has been added to the Test-Mode-1 data. Although the Test-Mode-1 data are noisy, they confirm the existence of a surface wave causing the normal mode altimeter track to lose lock.

Another example of retracking just prior to a loss-of-lock condition is shown in Figure 7. The dashed line depicts the elevations from the onboard tracker, and the solid line represents elevations resulting from retracking. These data are from revolution 1234 on September 21, 1978, over Antarctica in the vicinity of  $72.04^{\circ}$  S latitude and  $122.4^{\circ}$  E longitude. A surface wave at the 12 km mark is observed after the data were retracked; this surface wave is most probably the cause of loss-of-lock. AGC is shown at the bottom of Figure 7 and is observed to rise or fall corresponding to whether the ice surface elevation is rising or falling referenced to the tracking

Figure 6 - Comparison of Test-Mode-1  
Seasat Data and Normal Seasat  
Data over Greenland. Normal Mode  
Lost Lock at 14 km Mark. Test-  
Mode-1 Data Indicates Presence of  
Ice Surface Wave.

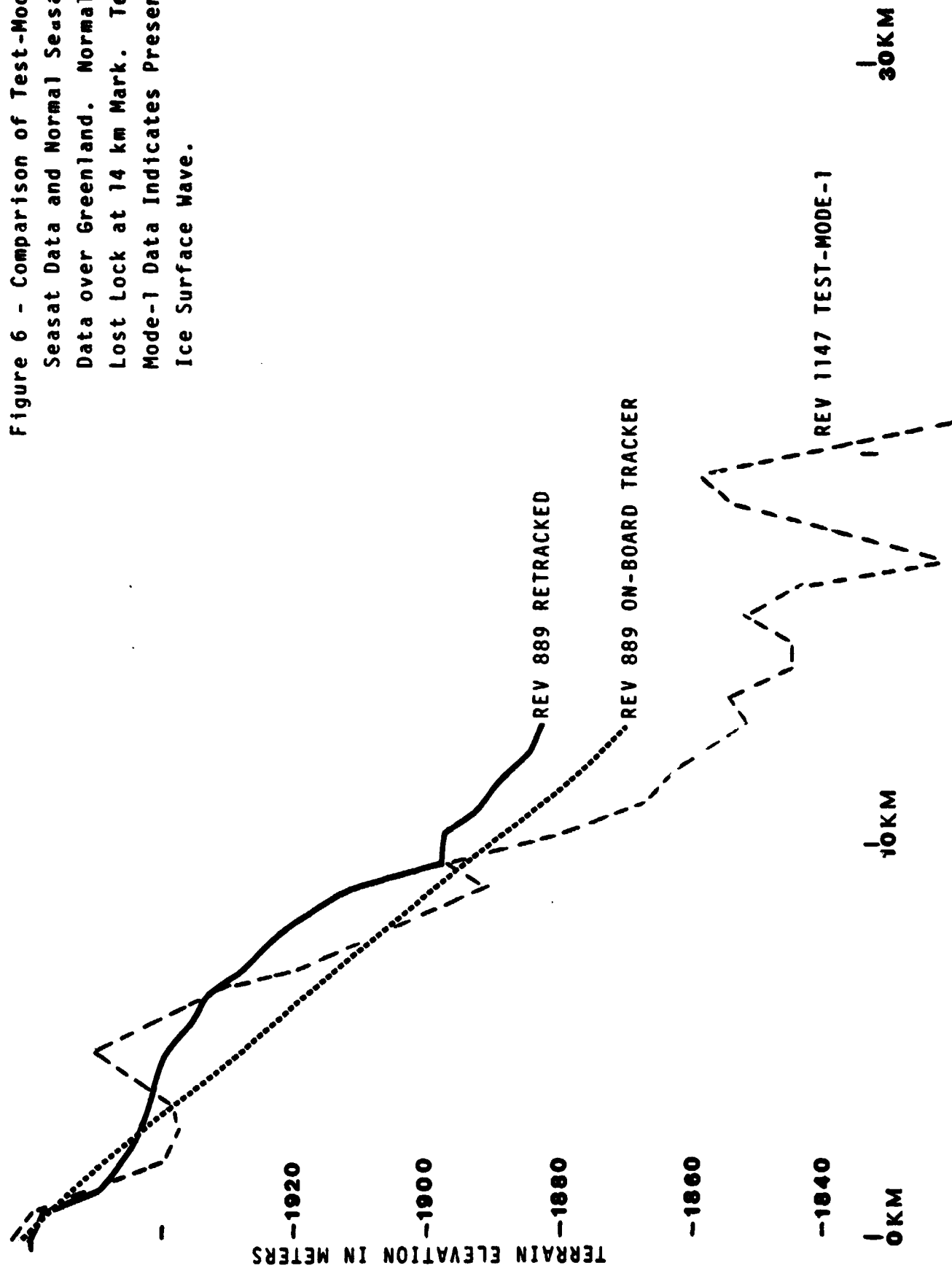
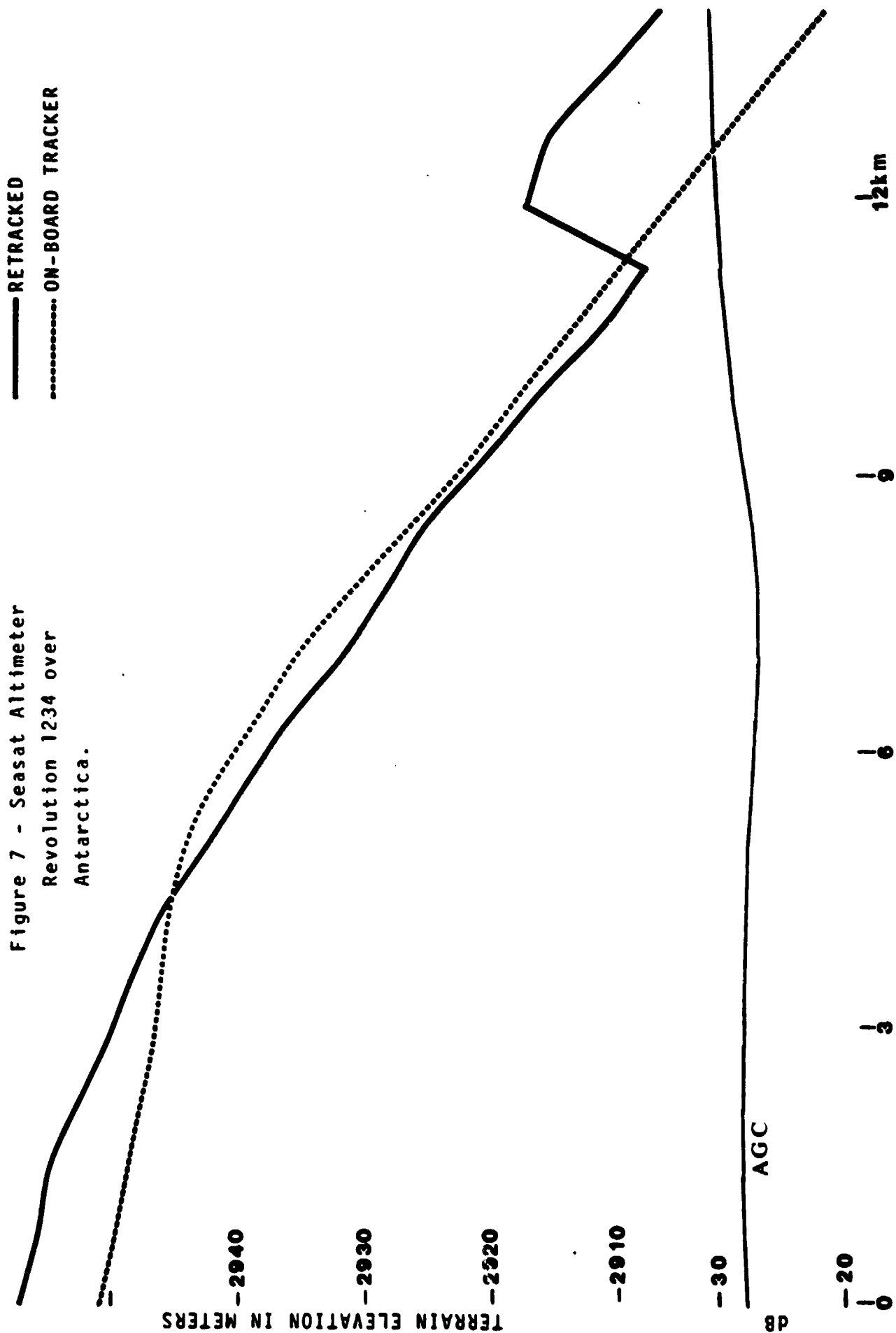


Figure 7 - Seasat Altimeter  
 Revolution 1234 over  
 Antarctica.



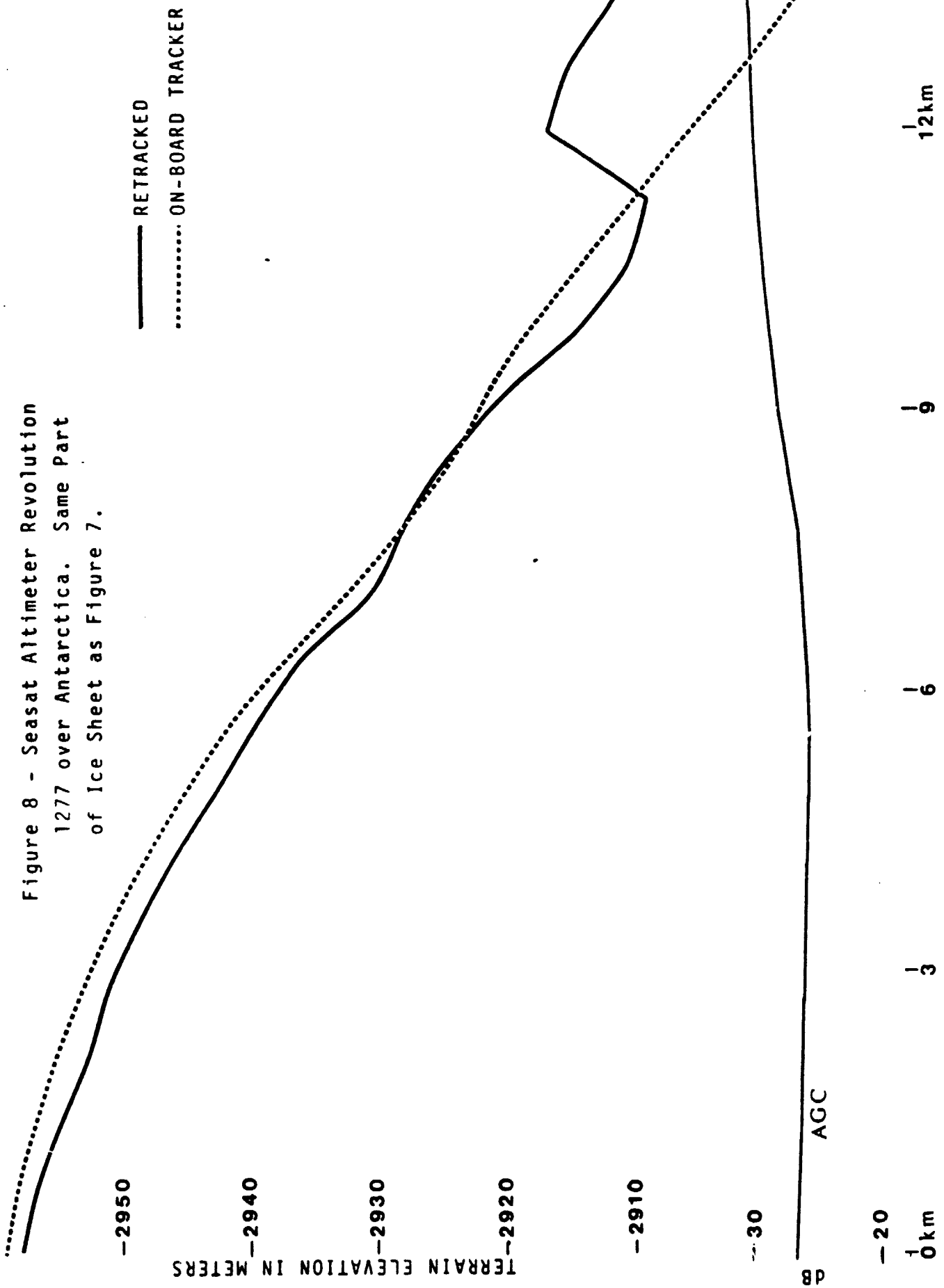
gate position.

It is fortuitous that only three days after revolution 1234, another Seasat pass, revolution 1277, traversed the same area of Antarctica. The groundtracks were parallel and were separated by only 25 m. The data sampling footprints from pass-to-pass had a 170 m separation. The results from revolution 1277, as shown in Figure 8, are presented in the same manner as Figure 7. Comparing the onboard tracker results from both revolutions, the surface elevations differ as much as 10 m. The retracked elevations agree within  $\pm 1$  m. The AGC levels in Figure 8 again rise or fall corresponding to whether the surface rises or lowers with respect to the tracking gate.

The next example of loss-of-lock (Figure 9) is accompanied by the 0.1 second waveforms. This Figure is a surface elevation plot for revolution 1277 in the vicinity of  $72.07^{\circ}\text{S}$ ,  $124.5^{\circ}\text{E}$  on the Antarctic ice sheet. The solid line is the elevations computed by retracking the waveforms, and again a surface wave feature causes the loss-of-lock. From left-to-right as indicated in Figure 9, there are 21 corresponding waveforms.

These 21 waveforms are shown in Figure 10 (presented on four pages). Waveforms 1 through 10 have waveform ramps fairly near the middle (tracking) gate, although retracking is still required. Starting with number 11, the waveforms move progressively to the left, towards an earlier return time. The concomitant decrease in amplitude is not the result of weaker surface returns, but is caused by the Seasat tracking system

Figure 8 - Seasat Altimeter Revolution  
1277 over Antarctica. Same Part  
of Ice Sheet as Figure 7.



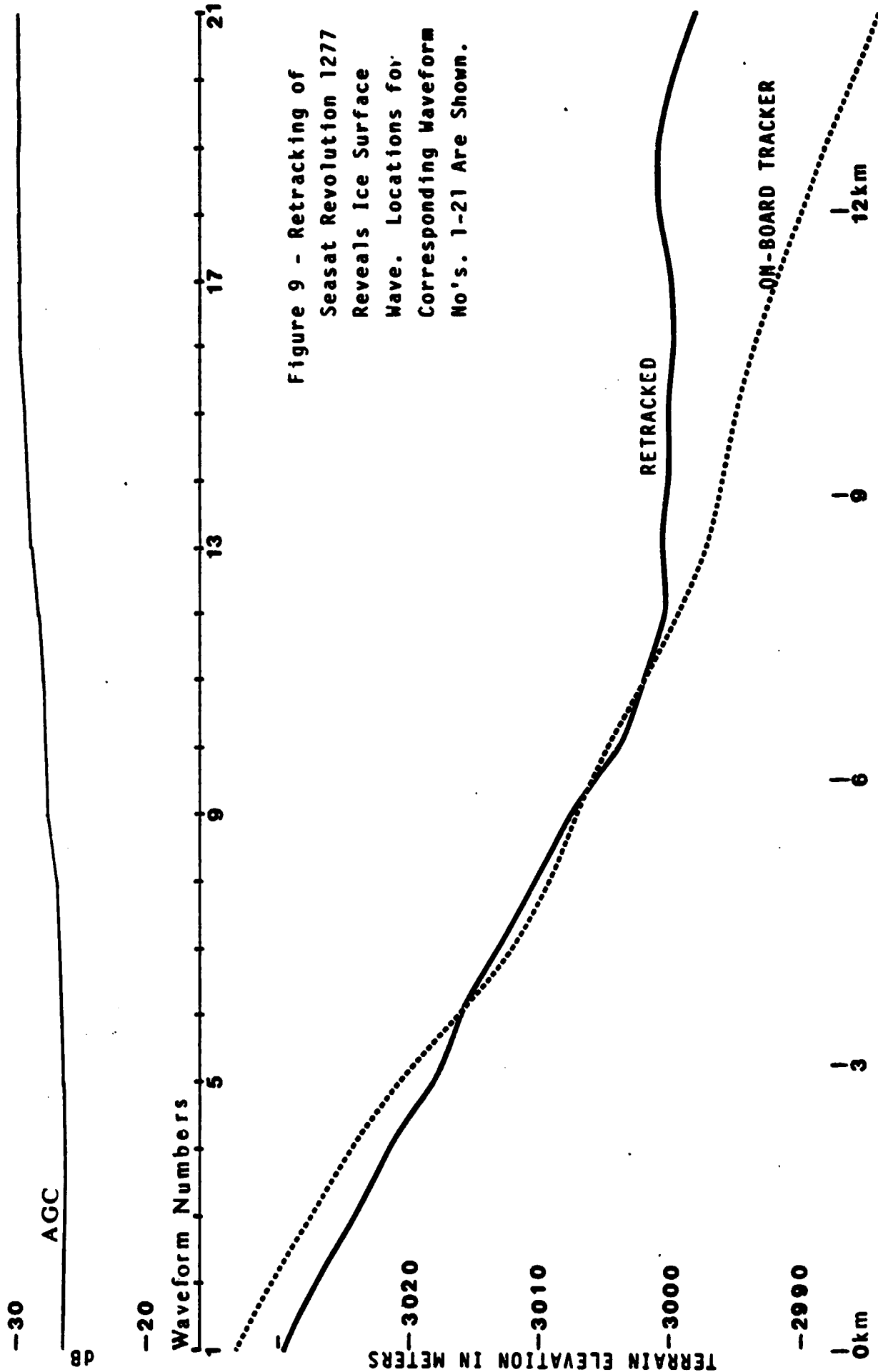


Figure 9 - Retracking of  
Seasat Revolution 1277  
Reveals Ice Surface  
Wave. Locations for  
Corresponding Waveform  
No's. 1-21 Are Shown.

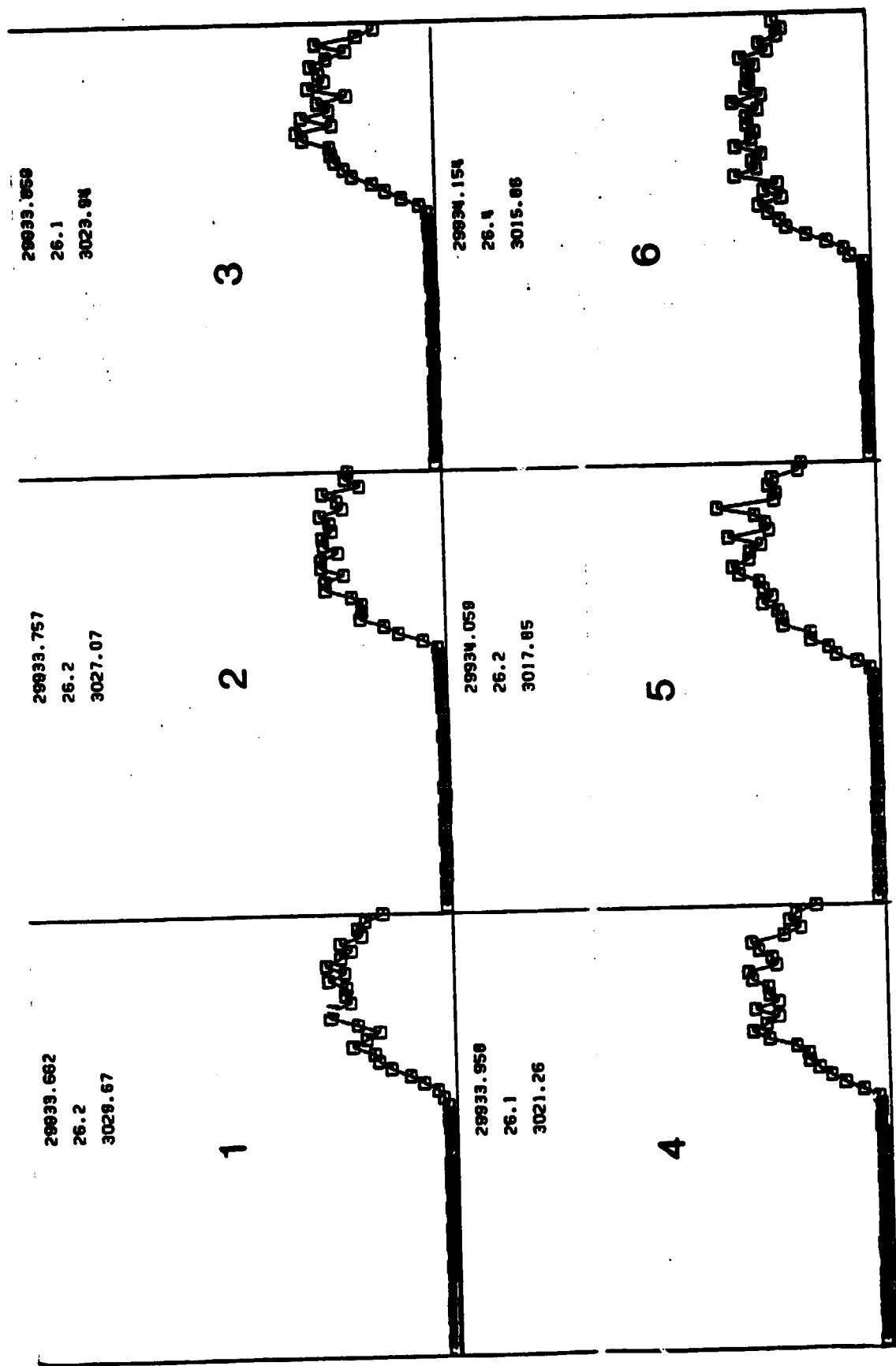


Figure 10 - Waveforms 1-21  
Corresponding to Figure  
9 Surface Elevations

(continued)

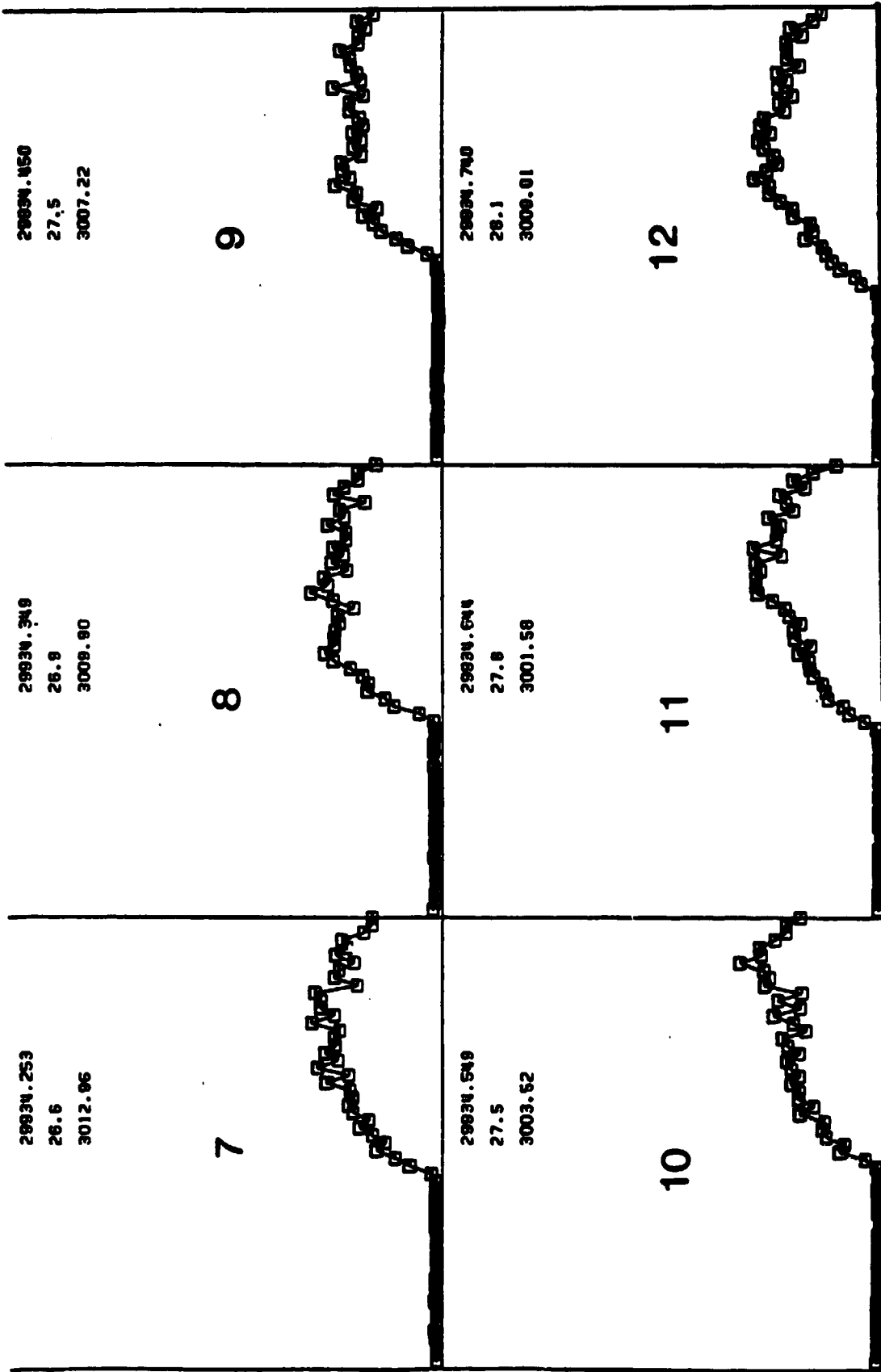


Figure 10

(continued)



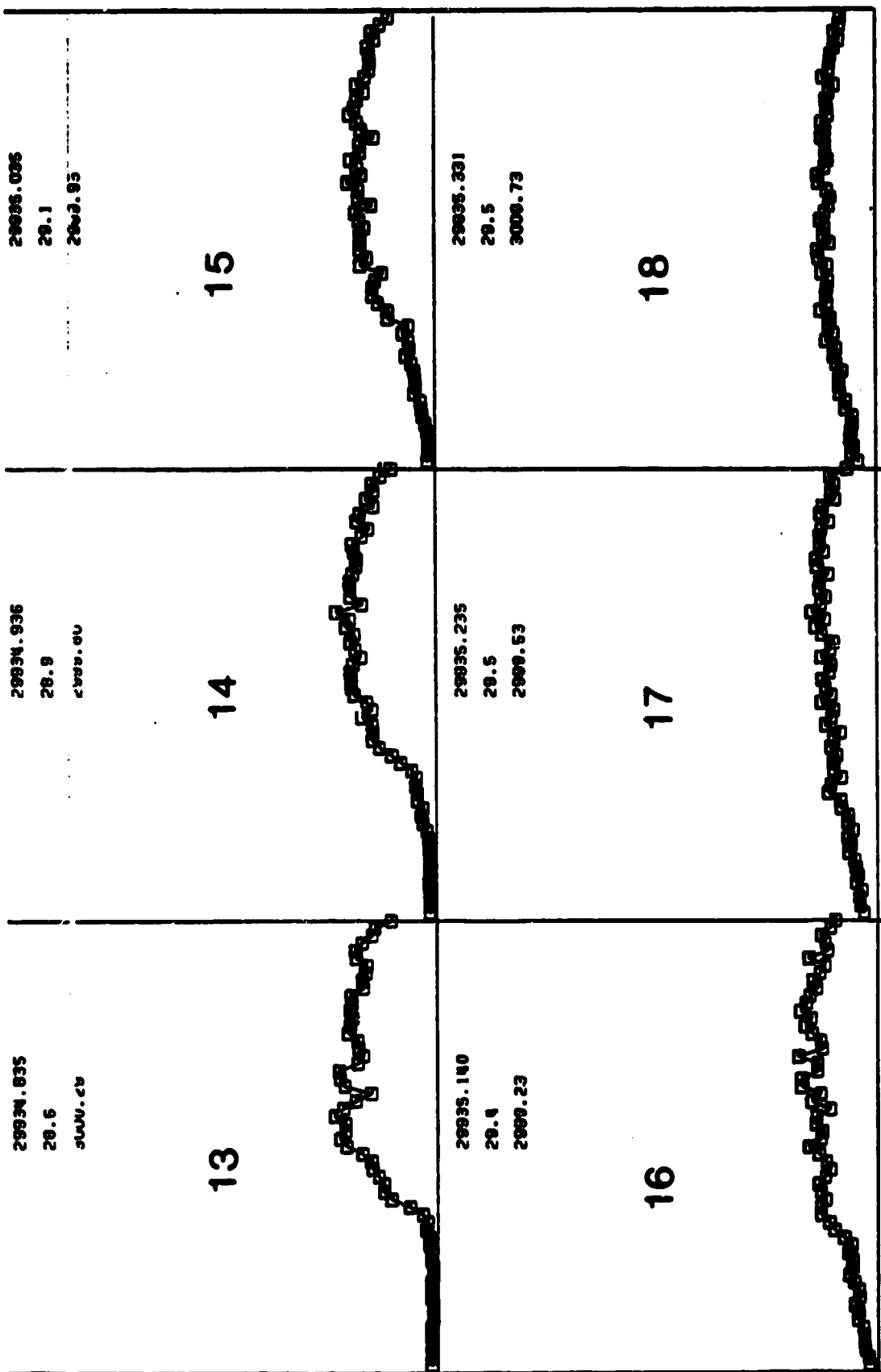


Figure 10

(continued)

<p>29935.432</p> <p>29.5</p> <p>3000.54</p>	<p>29935.527</p> <p>29.5</p> <p>2999.76</p>	<p>29935.626</p> <p>29.5</p> <p>2997.56</p>
19	20	21

Figure 10

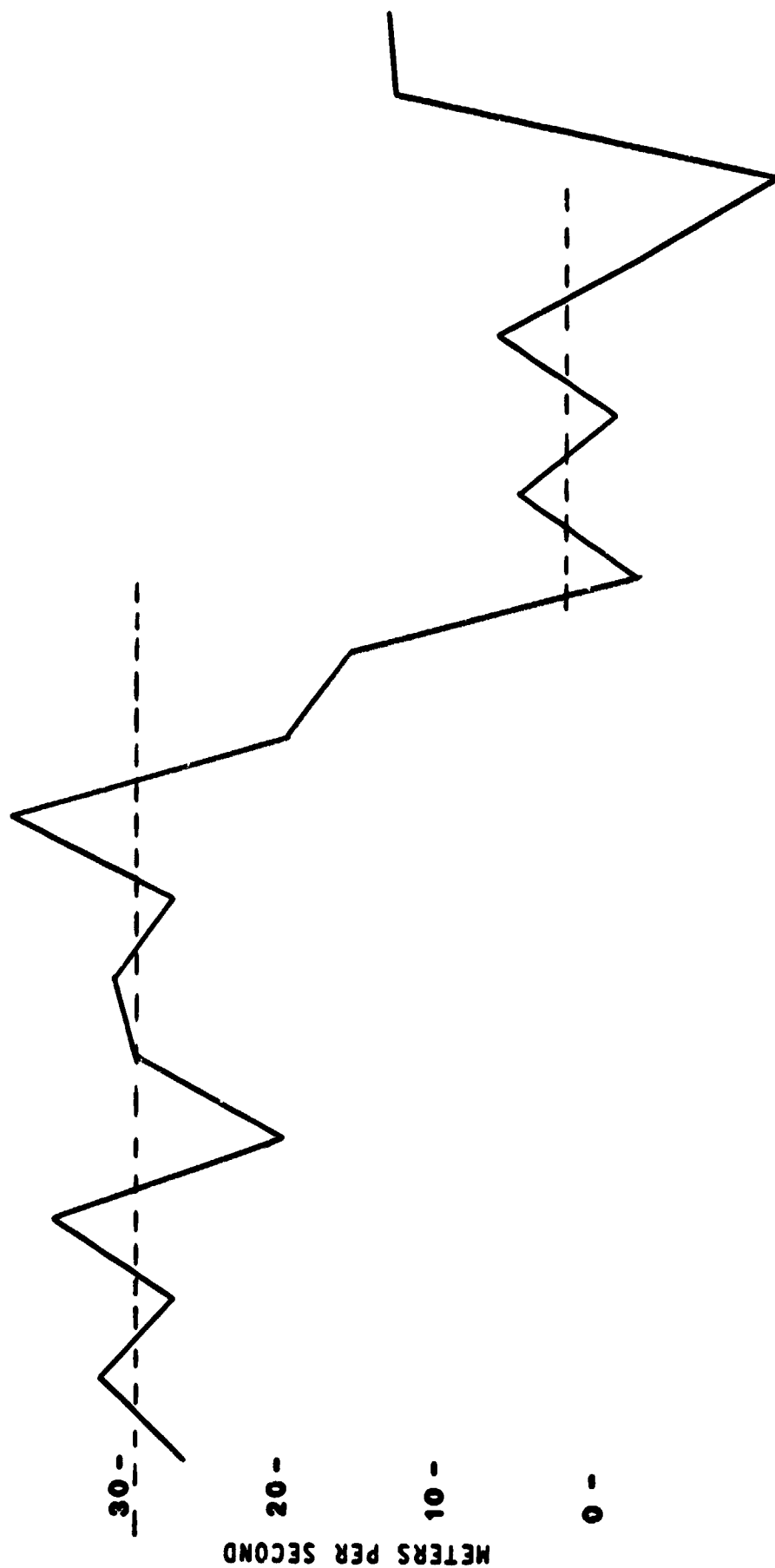
(conclusion)

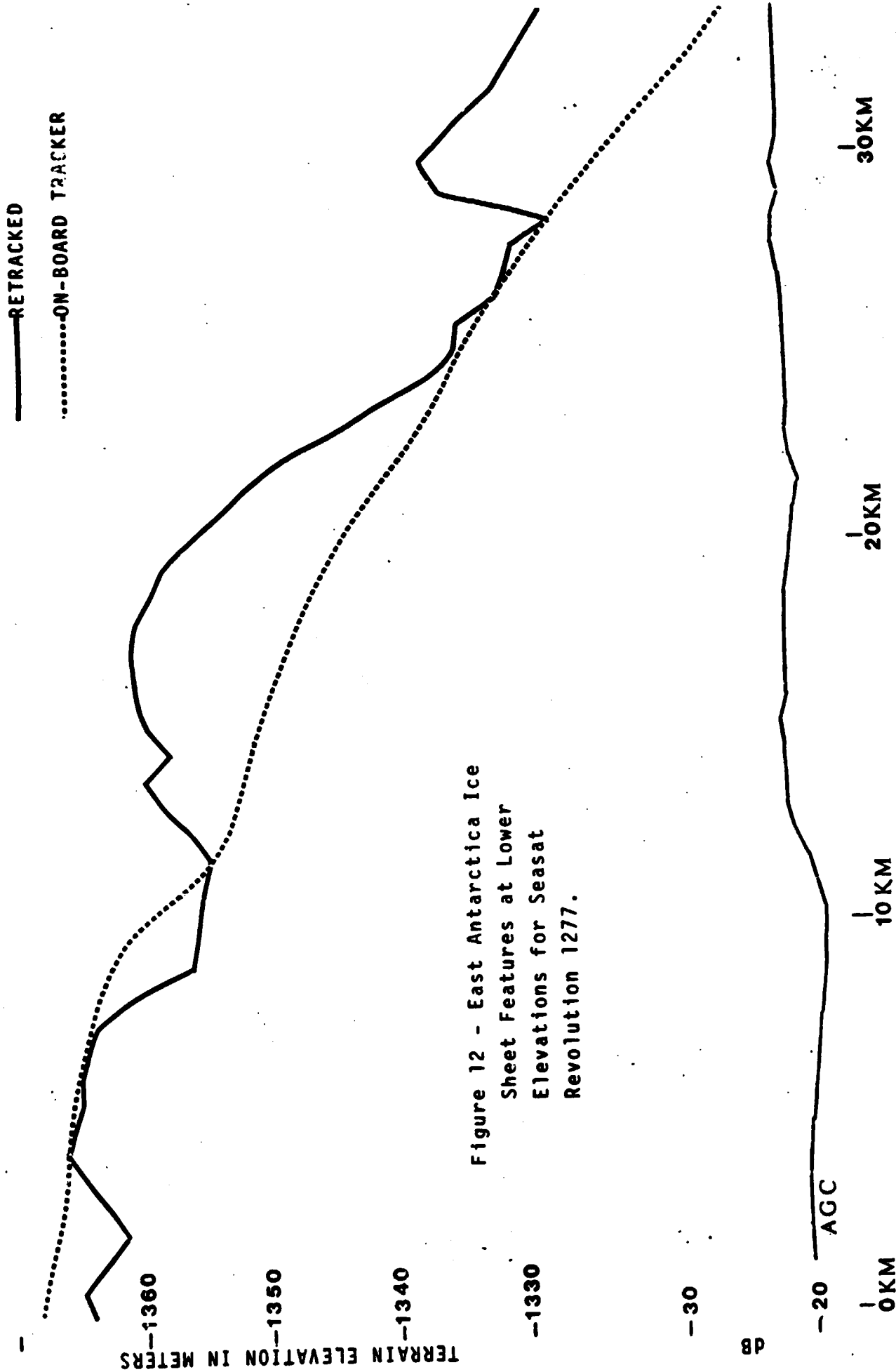
scaling the stored waveforms to make the areas under the waveforms constant; post-flight waveform rescaling by Hayne (personal communication) affirms this conclusion. The Seasat tracker did not indicate loss-of-lock status until 0.6 seconds after waveform number 21.

The altimeter range velocity for the Figure 9 surface elevations is plotted in Figure 11. The first portion shows a velocity of approximately 29 m/sec; the latter portion has a mean velocity of about 2 m/sec. The velocity change (acceleration) near the center of the Figure is thus 27 m/sec over a 0.3 second interval, or 90 m/sec<sup>2</sup>.

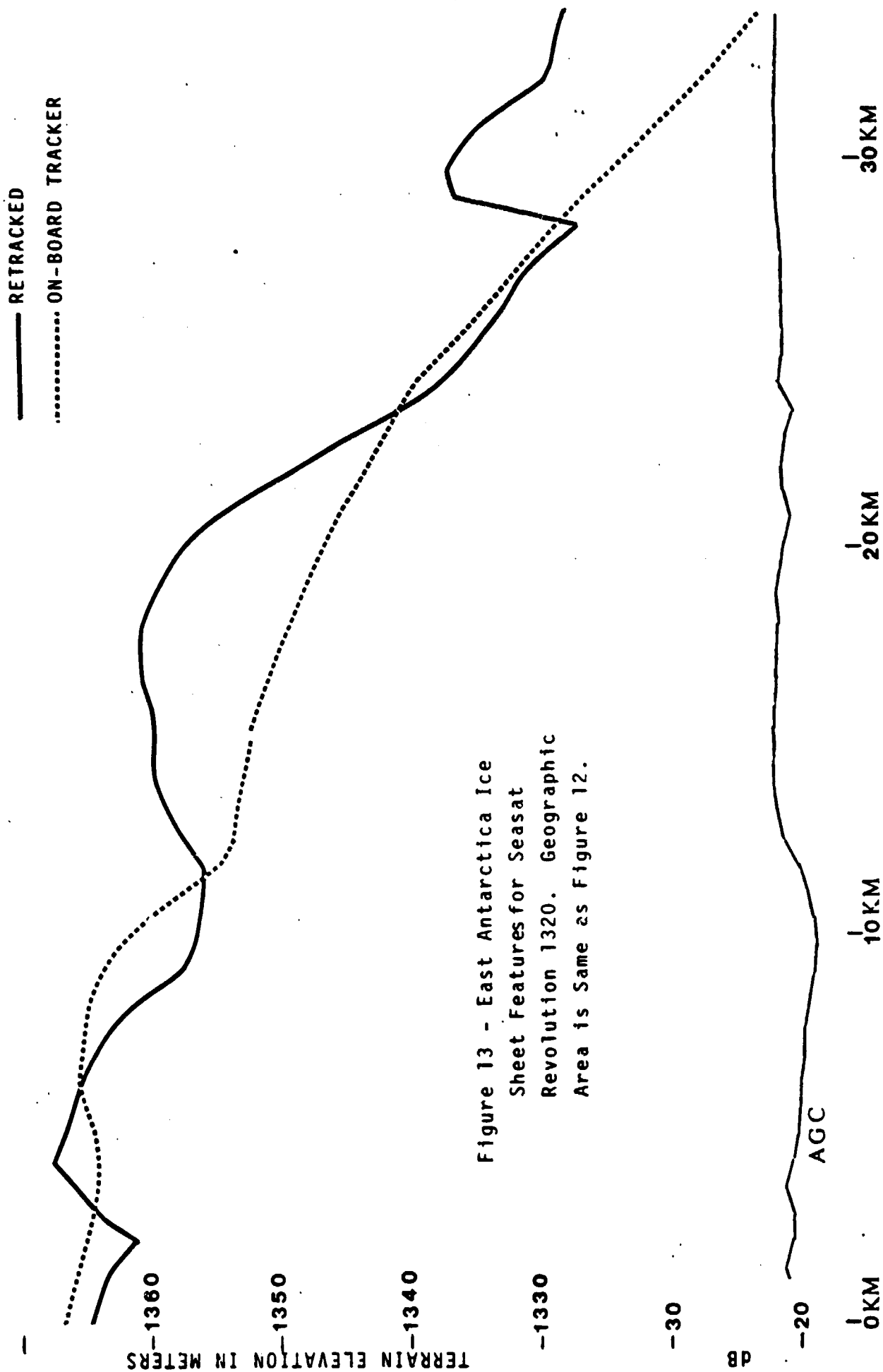
This high level of acceleration is not of itself the cause of the loss-of-lock, although it greatly ( by two orders of magnitude) exceeds the response capability of the tracker. The accumulated error has to exceed 14.05 m ( 30 gates x 0.4684 m/gate ) before the waveform ramp exits the waveform sampling gates. This is illustrated in Figure 12 where another portion of revolution 1277 over Antarctica, at a much lower elevation, has been retracked. Near the 11 km mark, retracking the waveforms reveals a surface wave causing a range acceleration of about 25 m/sec<sup>2</sup>. The error (true surface versus tracking point) builds up to 12 meters in this example, then the true surface elevation slopes in the direction of the tracker-computed surface and they converge, thus maintaining lock. Another surface wave appears at the 28 km mark; in this instance the error buildup exceeded 14.05 m and the altimeter lost lock.

Figure 11 - Altimeter Range Velocity  
for Figure 9 Surface Elevations.





The increase in the frequency of surface waves as shown in Figure 12 is typical of lower elevations of the ice sheets. Seasat revolution 1320 traversed these same ice features three days after revolution 1277. These parallel groundtracks had a crosstrack separation of 35 m; the data sampling footprints were separated pass-to-pass by 100 m. The result of retracking revolution 1320 is illustrated in Figure 13. The ice features in Figure 13, after retracking, replicate the ice features in Figure 12 to better than the 1 m level, and lend additional credence to the retracking algorithm.



## **CONCLUSIONS**

Analysis of the existing Seasat altimeter data base over the Greenland and Antarctic ice sheets is a crucial part of designing a future improved altimeter tracking capability over ice sheets. Retracking of the waveforms provides valuable information concerning wavelength and amplitude of ice sheet surface features that future satellite altimeters will encounter and must measure.

It is recommended that additional Seasat altimeter waveform retracking be performed in a systematic manner to characterize ice sheet topography as a function of geographic area and elevation.



## **ACKNOWLEDGEMENTS**

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